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Factors Affecting Cost of Geothermal Power Development and Production

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Keywords
Cost of geothermal power, capital cost, operation and maintenance costs

ABSTRACT

Geothermal power development and production consists of a succession of phases whose cost is affected by a series of factors and parameters. A clear distinction is usually made between the three major development phases – exploration, confirmation, and site development – which are followed by the power production phase. The kind of factors influencing the cost of each phase depends on the nature of the activities it comprises. Three major kinds of factors may be distinguished: (1) the site and resource characteristics, (2) the project type, size and the quality of its design, and (3) the market conditions. Since each phase is more or less affected by one or more of these parameters, the resulting power production costs are quite project-specific. In order to enable any stakeholder to have a better understanding of how these factors affect the cost of geothermal power, the following analysis details their respective impacts.

Introduction

The cost of geothermal power development and production is affected by various kinds of parameters. In order to better understand their respective effects, the following analysis identifies and explains how these factors influence the cost of geothermal power. Since power facilities have an expected lifetime, power costs are usually expressed in “levelized cost of electricity.” Levelized cost of energy corresponds to the cost of power that amortizes all capital costs incurred over the expected lifetime of the power plant. The initial capital costs and financial interests are thus spread out over the total amount of energy produced throughout the entire production life of the power facility. Levelized costs figures have two major components: (1) the levelized cost of the initial capital investment and (2) operation and maintenance costs. This article identifies and explains how site, resource, market, and project specific characteristics affect initial capital costs, and operation and maintenance (O&M) costs.

Geothermal Development: Initial Capital Investment and Cost of Money

Once the developer’s rights on the resource are secured, geothermal power development typically begins with an exploration phase to define the geothermal resource. The confirmation phase which follows, seeks to confirm the power production potential of the resource as well as the economic feasibility of the project. Once both these phases are successful, the site development phase may begin. Major components of the site development phase are well drilling, steam gathering, and power plant construction. Most projects also require the construction of additional transmission infrastructure to be connected to the grid. Various kinds of permits (e.g. environmental, construction, etc.) are required for these phases and the process to obtain them may result in significant cost increases for the project.

Exploration

Exploration seeks to locate a geothermal resource able to support power production at competitive cost. It consists of a succession of analyses combining geological, geophysical, and geochemical data and field surveys as well as other techniques (e.g. temperature gradient holes) that aim to verify the geothermal potential of a site, locate a resource, and identify the best spots to drill wells. Throughout the exploration phase, knowledge and understanding of the underground rock structure increases. Exploration should only be pursued if most of the information obtained confirms the power production potential of the site. The exploration phase ends either when one or two successful full size production wells are drilled or when the site is abandoned.
Exploration costs typically range from $100 to $250+ per kW installed with an average value of $150/kW. Cost values provided by this analysis are expressed in $ per kW installed. Since most expenses incurred during the various development phases are related to the size (projected power capacity) of the power plant, this approach allows to express cost independently of the project size. A series of factors, however, affects these costs. The project nature (greenfield vs. expansion) will determine the extent of the exploration program needed. Greenfield projects are power projects developed on new sites. Capital cost of greenfield projects are typically 10-15% higher than those of expansions due to higher infrastructure, exploration and interconnection costs. Expansions are power projects to be developed on well-known resources already supporting geothermal power plants.

Since drilling activities are the most expensive cost incurred during exploration, factors affecting drilling costs (i.e. resource depth, geology, etc.) have tremendous impact on the actual exploration costs. An extensive analysis of factors affecting drilling costs is provided in section A.3. Site characteristics (e.g. accessibility, topography, etc.) will also impact connection and infrastructure costs. The size of the project will determine how costs which are not related to the project capacity, may be spread out over a larger power output to achieve economies of scale. Since exploration is a rather risky activity, investors providing capital for this development phase require high rates of return. Drilling a geothermal well typically costs about $2.5 million and Wildcat (exploration) wells have a probability of success averaging 20-25%. In finance, investors tend to compensate risk with higher rates of return. Equity invested in geothermal exploration is venture capital that tends to require 18-22+% annually. As a result, the actual cost of exploration activities relies on the time required to build the entire project. Since it usually take about 3 to 6 years to bring a power plant online, the average actual cost of exploration when the power plant begins to produce power is $341/kW (i.e. the value of $150 on which a 20% interest rate is applied during 4.5 years). Any time delay in later development phases (e.g. due to permitting issues) has thus a tremendous impact on the resulting cost.

**Confirmation**

Since commercial banks or financial institution generally will not begin to consider lending money to geothermal developers until reservoir assessment reports prove that the resource is able to sustain power production, the developer has to drill additional production wells with venture capital or their own financial resources until 25% of the total production capacity needed for the project is verified. According to GeothermEx (2004), drilling constitutes 80% of the cost of the confirmation phase. Other activities include well testing and miscellaneous tasks. Factors affecting drilling costs are thus essential parameters in confirmation cost variability. Due to the nature of the capital involved (i.e. equity), any time delay in later development phase will significantly impact the actual cost of this development phase. Since the risk associated with confirmation activities is lower than that associated with exploration, capital invested in confirmation tends to require a slightly lower rate of return. Confirmation costs typical average $150/kW.

**Site Development**

The site development phase covers all the remaining activities needed to bring the power plant online. It consists of drilling remaining production and injection wells and plant, steam gathering system and transmission requirements design and construction. Prior to these activities the developer will obtain or ensure he will be able to obtain all permits needed for each phase. While some permits are needed for the exploration phase, the permitting process mostly concerns the drilling and site development phases. Since the most important and costly permitting activities pertain to the site development phase, all permitting issues are addressed in this section.

**Permitting**

Geothermal power projects must comply with several legislative requirements related to the National Environmental Policy Act (NEPA). Generally speaking, the permitting process investigates a range of potential impacts of the project, i.e. potential archeological, cultural/religious and biological values at the site, local hydrology, etc. The kind and extent of studies required by the permitting process vary according to the legislation of each state. It may also depend on the size (power capacity) of the project as well as on the land owner (government vs. private). Environmental documents are prepared for agency decision-makers to provide them with information enabling them to decide whether to issue a permit or not. “Permitting” includes both environmental document preparation and obtaining permits. As suggested above, the cost of permitting may vary significantly according to state legislation, the size of the project, the nature of the site, the land owner, and opposition from local communities. Cost of permitting may thus range from $10 to $50+ per kW. However, the cost impact of permitting may be significantly larger if important time delays occur, thereby affecting the cost of previous development phases financed with equity capital.

**Drilling**

Drilling costs are overwhelmingly influenced by the resource characteristics and learning effects. However, market parameters may also impact the cost of this activity. Some resource characteristics affect the cost of individual wells while others affect the number of wells to drill. Major parameters affecting the cost of one well are (1) the depth and thickness of the resource, (2) the diameter of the well, (3) the pressure (well blow-out prevention) and geology of the rock formation, and (4) the chemistry of the resource (special alloy casing/liner requirements). The geologic structure of the rock formation determines the intensity and frequency of the “loss of circulation fluid” problems, which along with rock hardness, well diameter and resource depth, influence the time required to drill the well. Hypersaline (corrosive) brines may require titanium liners which may double the average cost of a well. As a
result, the cost of a geothermal well may vary from 1 to over 8 million dollars with an average cost figure of $2.5 million. On the other hand, the number of wells to be drilled depends on the average productivity of the wells. Resource temperature, pressure, and permeability are essential parameters influencing the well flow rate and thus its productivity. Resources characterized by moderate temperature (less than 400°F) are usually pumped to increase well productivity. Downhole pumps are sensitive to high temperature and their use is thus limited to resources below 400°F.

As the number of wells drilled at a particular site increases, the structure and characteristics of the geothermal resource are better understood (i.e. learning effects). As a result, the drilling crew is better able to site the well. The typical drilling success ratios increase from 25% during exploration to 60% during confirmation and to 80% during the site development drilling phase. Additional savings occur since drillers can discard some options or precautions generally used for the first wells in the event they encounter specific drilling problems.

Market parameters may also affect drilling costs. This is particularly well illustrated by the volatility of drilling rig rental costs which fluctuate with energy prices. Since the geothermal industry competes with the oil and gas sector for the use of drilling rigs, higher oil prices mean more oil exploration and industry competes with the oil and gas sector for the use of drilling rigs rentals. This, however, will reduce the overall plant efficiency. When the power system efficiency improves, the system produces more energy with the same equipment. As a result, the specific cost (cost/energy output) of the power system decreases. This relationship determines the preferred technology (steam vs. binary). Steam power equipment is usually considered less expensive than binary equipment, but since the efficiency of a steam system declines sharply when the brine temperature falls below 400°F, binary power systems become competitive at brine temperatures around 350°F. The resource temperature is one of the most important factors affecting the cost of the power plant since the specific costs of the power system may vary by a factor of 2.5 according to the power plant efficiency.

Brine chemistry is another essential factor affecting the cost of power systems. The brine corrosiveness, scaling potential, non-condensable gas (NCG), and hydrogen sulfide (H₂S) content influence the construction material choice, the size of certain power plant components (condenser, vacuum system), and the well need for specific equipment (e.g. crystallizer-clarifier, abatement systems, etc.). Since the scaling potential of minerals contained in the brine depends on its temperature and pH, the power producer may choose to reduce the amount of heat extracted from the brine to reduce scaling problems. This, however, will reduce the overall plant efficiency.

Site Characteristics

Weather conditions and water availability are essential factors influencing the choice of the power plant heat extraction system. Water-cooled systems are considered less expensive, but when water is not readily available (e.g. binary systems in desert area), an air-cooled system may be the most economic option. Since steam power plants produce water in the condenser, this water is typically used in a water-cooled heat extraction system of geothermal steam power technologies. Harsh winter conditions (e.g. snow) may also induce delays in the construction period thereby impacting the cost of all prior expenses. Site topography and remoteness are other factors to consider as they may affect the cost of excavation, slope stabilization and infrastructure connection (e.g. roads, transmission, etc.).

Transmission

Some geothermal projects require constructing costly transmission lines in order to be connected to the grid. The length and capacity of the transmission line as well as the topography of the area are key parameters affecting the cost of this phase.

Power Plant Design and Construction

Power plant design is a complex activity that aims to minimize both construction and operation and maintenance costs over the lifetime of the power facility. It thus consists of defining the optimal size of power plant equipment and choosing the best fitted technologies and construction materials according to the site and resource characteristics.

Resource Characteristics

The temperature and chemistry of the resource are fundamental parameters affecting the power plant design and construction material choice. Brine temperature determines the overall efficiency of the power system and thus its cost. When the power system efficiency improves, the system produces more energy with the same equipment. As a result, the specific cost (cost/energy output) of the power system decreases. This relationship determines the preferred technology (steam vs. binary). Steam power equipment is usually considered less expensive than binary equipment, but since the efficiency of a steam system declines sharply when the brine temperature falls below 400°F, binary power systems become competitive at brine temperatures around 350°F. The resource temperature is one of the most important factors affecting the cost of the power plant since the specific costs of the power system may vary by a factor of 2.5 according to the power plant efficiency.

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Other Site Development Costs

Steam Gathering System

The steam gathering system consists of the network of pipes connecting the power plant with all production and injection wells. Its cost varies significantly according to the site spread, topography, and accessibility. The chemistry of the brine may also impact the type of material used to collect and sometimes process the brine. Important differences appear between dry steam, flash steam, and binary power systems. The resulting cost ranges from $50 to over $400+ per kW. A reasonable average cost figure is $250 per kW.
Important economies of scale apply to large projects since they may spread transmission costs over a larger power output. Permitting issues related to transmission line construction may also be costly and delay the entire project.

Economies of Scale

Economies of scale have an important impact on geothermal power development costs. Sanyal (2004) estimated and modeled their impact with the following relationship:

$$ CC = 2500e^{-0.0025(P - 5)} $$

where CC corresponds to capital costs and P represents the project’s power capacity. Figure 1 illustrates the evolution of geothermal projects’ capital costs according to their power capacity.

**Figure 1.** Effect of economies of scale on power plant capital costs.

Land, Labor, Raw Materials and Soft Costs

Land costs are a complex issue that usually differentiate between surface and subsurface costs. Surface costs are usually low while subsurface costs (royalties) may constitute considerable amounts. Since royalties concern the power production phase, they will be addressed in the O&M cost section. Generally speaking, geothermal developers tend to lease land rights.

Since labor costs typically account for 40% of total costs, they are a major cost component of power projects. However, labor costs haven’t increased much during the last 20 years. Equipment and raw material costs typically constitute another 40% of the project’s cost. These costs are particularly vulnerable to market prices and may considerably affect the resulting cost of the project. Current oil, steel and other construction material prices are good examples of this evolution. Site remoteness and accessibility may also increase labor costs 8-12% if construction camps have to be built (Bloomquist, 2002).

Soft costs encompass a series of costs related to project development and financial issues. They typically include engineering, legal, regulatory, reporting activities, and financial fees, and corresponds to 6-8% of total project’s expenditures. Note that developers also incorporate provisions for contingencies (i.e. typically 10% of the budgeted costs) and amortize any previous failed exploration costs on successful projects.

### Financial Factors

Interest rates and debt length are crucial parameters affecting the cost of geothermal power. As suggested in the exploration and confirmation sections, time delays have important impacts on investments that require high rates of return. Geothermal projects are typically financed by a mixture of equity (capital exposed to important risks and requiring high rate of returns) and debt (capital much less exposed to risky and characterized by lower interest rates). The financial structure of geothermal projects is usually composed of 25-30% equity (that, on average, require an 18% annual rate of return) and 70-75% debt (with a 7% interest rate). B. Owens (2002) also provides further insight about how equity’s rate of return and debt interest rate determines the optimal capital structure and affect the minimal cost of power. Developers have a great preference for debt financing but commercial banks usually require a minimum of 25% equity to be involved in order to secure their investment.

The nature of the project developer also has an important impact on the costs of money. The *Renewable Energy Technology Characterization* report (1997) distinguishes four types of developers characterized by a different access to financial resources: (1) municipal utilities (MU), (2) regulated investor owned utilities (RIOU), (3) generating companies (GC) and (4) independent power producers (IPP). “*Renewable Energy Technology Characterization,*** Electric Power Research Institute, Office of Power Technologies & US DOE’s Energy Efficiency and Renewable Energy, 1997. As a consequence, typical financial conditions accessible to IPP result in a cost of power at least 48% higher than that produced by MU. This figure assumes O&M costs of 2.2 €/kWh. As illustrated in Figure 2, this cost increase reaches 89% for the capital cost component (LCCI) of the levelized cost of energy (LCOE) and is exclusively related to interest rates and debt length.

### Operation and Maintenance Costs

Operation and maintenance (O&M) costs include all costs incurred during the power production phase. Operation costs typically comprise labor, consumable goods costs, and other miscellaneous charges related to daily power plant operation. Labor cost is a major component of O&M costs and is significantly affected by the size of the power plant. Labor requirements of geothermal power plants are subject to important economies of scale. Parasitic load (e.g. pumps and fans of cooling system) or chemical costs (e.g. air abatement, scaling control, or biotic water treatment) are specific to the power plant and site and may have significant cost impacts.

Maintenance costs are all expenses related to the power plant and steam field maintenance to keep the power facility in good working order. Such activities consist of machinery overhaul, building, power equipment, steam pipes and road repair, well rework, etc. Another essential maintenance activity is make-up drilling. This activity aims to compensate natural well productivity decline related to resource pressure and/or temperature drop.
or scaling issues. New production wells allow the maintenance of power production at full capacity and therefore keep the overall power production costs at reasonable levels. Although power producers consider make-up drilling costs as capital expenses to be amortized over a certain period of time, this analysis considers them as maintenance costs that allow sustaining full power production capacity. Similarly to the power plant capacity factor, these parameters result in the spread out of fixed production costs over the entire power output.

Royalties paid to landlords and taxes are another important cost related to the power production phase. Typical royalty rates are 3 to 5% of the power producer growth revenue (price obtained from power sale) or 10 to 15% of O&M costs.

O&M costs are project-specific and vary greatly according to the power plant size (economies of scale), technological characteristics (e.g. power and cooling system), and site and resource characteristics (depth, chemistry, etc.). O&M costs typically range from 1 to over 3.5 cents per kWh produced and tend to increase throughout the power plant lifetime. An average O&M cost figure is 2.2 ¢/kWh.

Conclusions

The above analysis identifies the most important factors affecting the major cost components of geothermal power development and production. Among those factors, site and resource characteristics, project size, and nature as well as market parameters and financial conditions are the most important. Most factors will impact both the capital costs and the O&M expenses and the matrix presented in Appendix 1 summarizes the importance of their respective impact. Financial conditions are particularly interesting since they directly influence the amount of money the developer is willing to spend on power plant design and construction materials. In the past, important trade-offs have been made between initial capital costs and later O&M costs. As a result, some geothermal power plants have significant O&M costs and appear poorly efficient. However, part of these trade-offs may be explained by the high interest rate of the 1970’s which encouraged developers to minimize the initial capital costs invested. Other factors (e.g. lack of experience, short-term profit vision, etc.) however also explain this phenomenon.

Since future development will probably take place on resources more difficult to locate or exploit, it appears more appropriate to link geothermal power development costs as well as the amount of resources economically developable to the price of energy. Further growth of the industry will allow geothermal developers and power producers to learn how to deal with more difficult resources and help reduce production costs. It would also recreate a stable network of suppliers, ensure the transmission of the expert’s professional experience to a new generation of professionals, and thereby enhance the reliability of new project cost estimates.

References


SEE NEXT PAGE FOR APPENDIX 1
## APPENDIX 1

### FACTORS AFFECTING COSTS

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Legend: The number of "++" signs indicates the significance of each parameter. Brackets indicate that site-specific conditions may exacerbate this impact.

Note: Confirmation costs do not appear in this table but is overwhelmingly composed of drilling and exploration type of activities financed by equity. Confirmation usually costs about $150 per kW installed but its actual cost is strongly influenced by the cost of money and time delays.